Life Sciences in Space Research 10 (2016) 47–52

Contents lists available at ScienceDirect

Life Sciences in Space Research

journal homepage: www.elsevier.com/locate/lssr

Simulated sudden increase in geomagnetic activity and its effect on heart rate variability: Experimental verification of correlation studies

Joseph M. Caswell[a,b,*], Manraj Singh[c], Michael A. Persinger[a,b,c,d]

[a] Neuroscience Research Group, Laurentian University, Sudbury, Ontario, Canada
[b] Human Studies Program, Laurentian University, Sudbury, Ontario, Canada
[c] Behavioural Neuroscience Program, Laurentian University, Sudbury, Ontario, Canada
[d] Biomolecular Sciences Program, Laurentian University, Sudbury, Ontario, Canada

ARTICLE INFO

Article history:
Received 29 February 2016
Revised 28 June 2016
Accepted 4 August 2016

Keywords:
Heart rate variability
Space weather
Geomagnetic activity
Cardiovascular
Autonomic
Weak magnetic fields

ABSTRACT

Previous research investigating the potential influence of geomagnetic factors on human cardiovascular state has tended to converge upon similar inferences although the results remain relatively controversial. Furthermore, previous findings have remained essentially correlational without accompanying experimental verification. An exception to this was noted for human brain activity in a previous study employing experimental simulation of sudden geomagnetic impulses in order to assess correlational results that had demonstrated a relationship between geomagnetic perturbations and neuroelectrical parameters. The present study employed the same equipment in a similar procedure in order to validate previous findings of a geomagnetic-cardiovascular dynamic with electrocardiography and heart rate variability measures. Results indicated that potential magnetic field effects on frequency components of heart rate variability tended to overlap with previous correlational studies where low frequency power and the ratio between low and high frequency components of heart rate variability appeared affected. In the present study, a significant increase in these particular parameters was noted during geomagnetic simulation compared to baseline recordings.

© 2016 The Committee on Space Research (COSPAR). Published by Elsevier Ltd. All rights reserved.

1. Introduction

The potential role of space weather, especially geomagnetic activity, in human physiological systems has been demonstrated across a range of phenomena including endocrine activity (Breus et al., 2015) and brain activity (Mulligan et al., 2010; Saroka et al., 2014). Particularly relevant to the current study, previous researchers have shown that the cardiovascular system may also be susceptible to variations resulting from geomagnetic perturbation (Dimitrova et al., 2004, 2009; Stoupel, 1999). From a pathological perspective, geomagnetic storms may actually result in an increased occurrence of myocardial infarction (Kleimenova et al., 2007; Stoupel, 1999) where the observed relationships may be associated with geophysically-mediated changes in arterial blood pressure (Dimitrova, 2006, 2009; Papailiou et al., 2011).

Although indices of mean heart rate and blood pressure have typically been employed in heliobiological research on autonomic or cardiovascular activity, there have been relatively fewer studies using heart rate variability (HRV) (Cornélissen et al., 2002; Dimitrova et al., 2013; Otsuka et al., 2001a,b). A number of earlier results presented by Otsuka and colleagues have indicated that HRV tended to decrease in response to increased geomagnetic activity for a subarctic sample of healthy males (Otsuka et al., 2001a), and that the observation of a gradation for this biological response to geomagnetic activity in a subarctic region could implicate a form of human magnetoreception (Oinuma et al., 2002). Furthermore, magnetoreception was also inferred from a light-dark-mediated response of human participants to ultra-low frequency (ULF) Pc5 geomagnetic pulsations (Otsuka et al., 2001b). Finally, the application of an artificial magnetic field simulating ULF (~0.0016 Hz) geomagnetic pulsations with a weak intensity of ~50 nT appeared to decrease participants' HRV although this particular field application was 8 h in duration (Mitsutake et al., 2004). However, additional research has also implicated higher frequency Pc1 pulsations in geomagnetic-modulated variations of HRV (Kleimenova et al., 2007) and the current study used applied magnetic fields within this range (~0.20–4 Hz). Of further interest are the results obtained by Dimitrova et al. (2013) which identified significant changes (often decreases) in total variability and various frequency components of HRV including the ratio between low frequency and high frequency power which was interpreted as the balance between

* Corresponding author at: Behavioural Neuroscience, Laurentian University, Sudbury, Ontario, Canada P3E 2C6.
E-mail address: jx_caswell@laurentian.ca, neuraljc@gmail.com (J.M. Caswell).

http://dx.doi.org/10.1016/j.lssr.2016.08.001
2214-5524/© 2016 The Committee on Space Research (COSPAR). Published by Elsevier Ltd. All rights reserved.

autonomic branches (i.e., sympathetic and parasympathetic contributions to HRV). However, the authors (Dimitrova et al., 2013) also suggested that there was a degree of variation regarding how individuals accommodated geomagnetic changes with respect to autonomic-cardiovascular state.

Despite these conclusions, it should be noted that Billman (2013), after a thorough review of the relevant literature, determined that the low frequency to high frequency ratio of HRV does not reflect an evenly balanced system of influence. Rather, the low frequency component appears to be relatively ambiguous regarding specific autonomic contributions, which may be largely cholinergic in origin, while the high frequency component is more likely dominated by parasympathetic (e.g., vagal) effects. The author (Billman, 2013) derived an overall relationship of low frequency (*LF*) to high frequency (*HF*) activity with their relative autonomic contributions in arbitrary units (1 = baseline activity) following the relationship:

$$\frac{LF}{HF} = \frac{0.5\ \mathrm{PSNS} + 0.25\ \mathrm{SNS}}{0.9\ \mathrm{PSNS} + 0.1\ \mathrm{SNS}}$$

where PSNS = relative parasympathetic nervous system contribution, and SNS = relative sympathetic nervous system contribution.

Of greater importance for the field of heliobiology overall, a vast majority of relevant studies are inherently correlational in nature due to the independent measures of interest. Although related research has tended to converge upon similar conclusions regarding an effect of geomagnetic activity on human physiology, there is a persistent need for experimental verification of these effects. As an example, Mulligan et al. (2010) had earlier corroborated results revealed by Babayev and Allahverdiyeva (2007) regarding an influence of geomagnetic processes on neuroelectrical activity using correlational means. Following this, the inferences were validated through experimental simulation of sudden geomagnetic increases during electroencephalographic (EEG) recording (Mulligan and Persinger, 2012). Although cardiovascular activity has often demonstrated similar relationships throughout past investigations, there has yet to be experimental verification of this potential influence from a range of magnetic field configurations, particularly various frequency components.

One of the potential concerns regarding the use of magnetic fields in physiological research is the weak intensity of the applied field relative to other well-known electromagnetic sources such as magnetic resonance imaging (MRI) which employs much stronger fields in the Tesla range. However, imaging studies often required Tesla-level magnetic fields in order to discern sufficient detail from signals generated by the alterations in spin of protons. In contrast, the current experiment was involved with simulating natural conditions that disrupt essential physiological conditions (Dimitrova, 2004, 2006). There are multiple correlational studies that have shown reliable associations between the types of cardiac features we measured and natural geomagnetic activity within the 20–200 nT range (Babayev and Allahverdiyeva, 2007; Breus et al., 2015; Cornélissen et al., 2002; Dimitrova et al., 2009; Mulligan et al., 2010; Oinuma et al., 2002; Papailiou et al., 2011; Saroka et al., 2014). Furthermore, Mitsutake et al. (2004) similarly observed cardiovascular effects resulting from application of a temporally-patterned magnetic field of only 50 nT. The temporal pattern of the applied field used in the current study was constructed to optimally influence "physiological patterns". We have found that the more proximal the temporal pattern of the applied field is to the intrinsic patterns of cellular electrical activity the less intensity that is required to produce measurable disruptions (Lagace et al., 2009; Mach and Persinger, 2009). For example, a similar phenomenon was described for the most effective simulation patterns for inducing neuronal long-term potentiation (LTP) across different layers of the entorhinal cortices (Yun et al., 2002). This is consistent with the concept of natural resonance.

There are mechanisms other than Faradic induction of potential differences by which weak, physiologically patterned (that is non-temporally symmetrical shapes such as sine waves and square waves) magnetic fields applied through the body can produce significant influence upon function. Persinger and Saroka (2013) showed that the types of experiences induced in patients whose temporal lobes were stimulated surgically by millampere electric currents were comparable to normal volunteers who were exposed transcerebrally to microtesla magnetic fields. Estimates of the current induced within cerebral tissue by the surgical currents and the energy within the cerebral volume associated with the applied magnetic field produced almost identical effective values.

The integral duration and amplitude modulations of the field configuration we employed was simulated from the amplitude displacements associated with sudden storm commencements. The construct validity of this pattern was indicated by the similarity of the effect sizes for the onset of spontaneous seizures in epileptic rats when it was applied experimentally and the background values when natural fields occurred intermittently (Michaud and Persinger, 1985). The specificity of the shape and intensity of this experimentally generated field has been shown in other settings. For example rats developing experimental forms of a demyelinating disease displayed marked attenuation of symptoms when the base frequency of the applied field was 7 Hz and the serial changes in amplitude modulations was less than 40 nT with millihertz intrinsic periodicities (Cook et al., 2000). Application of the same field at 400 nT or application of 40 nT with 40 Hz oscillations or the latter with 400 nT produced effects that did not differ from sham field exposures. The primary goal of the current study was to employ similar geomagnetic simulation hardware used in verification studies by Mulligan and Persinger (2012) and also recently applied elsewhere for geomagnetic simulation (Murugan et al., 2013) in order to verify the apparent effect of geomagnetic increases on autonomic-cardiovascular activity determined by HRV measures.

2. Methods

2.1. Participants

After receiving ethics approval from the Laurentian University Research Ethics Board (LU REB), a total of 23 individuals volunteered for the current study. Exclusion criteria included <18 years of age, history of hypertension or other known cardiovascular health issues including arrhythmia or presence of a pacemaker ($n = 2$ excluded). Short-term electrocardiograph (ECG) recordings were obtained from a sample of 21 healthy volunteers (12 males, 9 females) from 18 to 55 years of age during both control and experimental conditions in a simple counterbalanced repeated-measures design. However, a single male ECG record was rejected for further analysis given the large number of artifacts (final sample of $n = 20$). Recording was done while participants were seated comfortably and during normal spontaneous breathing within a Faraday cage.

2.2. Data recording and processing

Single-lead (two electrodes) Covidien Kendall H135SG disposable ECG electrodes were used for all recordings with a Mitsar-201 amplifier connected to a laptop computer. WinEEG v2.103.7 software was used for data collection at a sampling rate of 250 Hz. All data were exported for further processing and analysis using additional software. Automatic QRS detection and computation of *R–R* intervals in milliseconds was conducted with ARTiiFACT v2.05 (Kaufmann et al., 2011). All records were further verified manually for accurate identification of waveform peaks. Any artifacts were corrected using a cubic spline interpolation of *R–R* intervals.

The HRV analysis suite within ARTiiFACT was used to calculate standard time domain indices of interest in milliseconds including the standard deviation of *R–R* intervals (*SDNN*) which indicates long-term variability, and the root mean square of successive differences between intervals (*RMSSD*) which indicates short-term variability. Time series resampling (4 Hz interpolation) and detrending was also conducted within ARTiiFACT along with fast Fourier transform (FFT) for very low frequency (*VLF* = 0.003–0.04 Hz), low frequency (*LF* = 0.04–0.15 Hz), and high frequency (*HF* = 0.15–0.40 Hz) components of HRV in power spectral densities of ms^2, as well as the commonly used *LF/HF* ratio.

2.3. Statistical analyses

Statistical analyses were conducted with SPSS v17 software including both parametric and nonparametric techniques, while Matlab v7.12 was employed for wavelet transform of magnetic field measures with a Morlet mother wavelet function using scripts created by Grinsted et al. (2004; Jevrejeva et al., 2003). Wavelet power probability estimates were also computed through comparison with red-noise (AR1) spectra. The appropriateness of this method for null hypothesis testing was verified by comparing the power decay of red-noise with that of a given time series of interest after Burg algorithm spectral analysis. Magnetic field data were standardized and zero-padded prior to time–frequency analysis with wavelet transform. Descriptive statistics of HRV variables were computed for each condition followed by application of Shapiro–Wilks test to check for normal distributions. Experimental conditions were compared using either paired *t*-test or Wilcoxon signed rank test as determined by the presence or absence of normally distributed data respectively, with statistical significance considered for $p < 0.05$. Median box-plots for significant results were produced using Matlab software. To further explore potential gender effects, data were transformed using a natural logarithm to accommodate parametric repeated-measures analysis of variance (ANOVA) in SPSS.

2.4. Magnetic field application

Sudden increases in geomagnetic activity were simulated using two custom rectangular coils (about 1.15 m × 1.15 m) placed on either side of the participant seating area ~1 m apart and ~35 cm away from the body proper. The waveform used was designed to imitate sudden geomagnetic impulses with individual point durations of 69 ms each separated by 1 ms. The resultant magnetic field was produced using a DOS PC system with Complex2 software designed by Prof. Stan Koren. Each point in the waveform ranges from 0 to 256 and is converted to an equivalent voltage (-5 to +5 mV) through a custom digital-to-analogue converter (DAC). An associated current is then delivered through the rectangular coils to produce the field.

Further investigation of magnetic field dynamics was undertaken using a MEDA FVM-400 Vector Fluxgate Magnetometer measured on three axes (*X, Y*, and *Z*) at a sample rate of 0.10 Hz (10/s). The field recording was acquired from the approximate location of the chest of a seated participant where the *X* and *Z* components did not demonstrate discernible periodicities as determined by both FFT and wavelet transform. The horizontal (front-to-back) *X* plane had an average intensity of 4750 nT (minimum = 4743 nT, maximum = 4757 nT) during field presentation with no significant change from baseline activity. The vertical *Z* plane also did not show a prominent change from normal background conditions with an observed average intensity of 19343 nT (minimum = 19338 nT, maximum = 19349 nT). Although the average intensity of the horizontal (side-to-side) *Y* axis during magnetic field presentation remained relatively minimal (*mean* = 775 nT), there were distinct

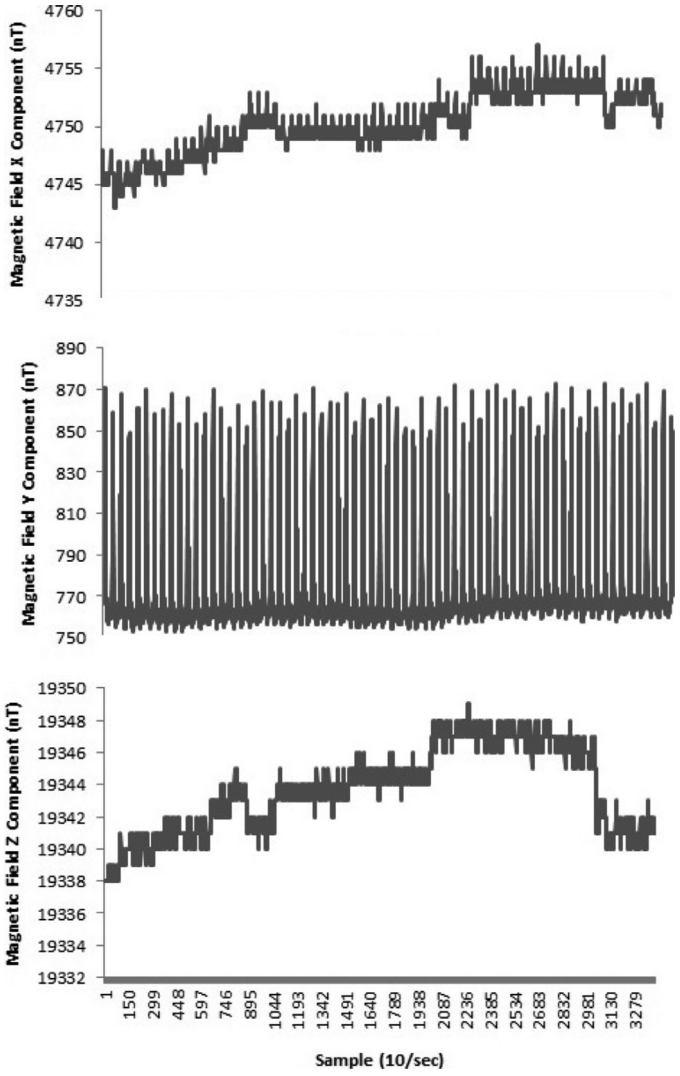

Fig. 1. Raw time series of sample magnetic field recordings from *X, Y*, and *Z* axes.

and periodic spikes above background levels by ~20–100 nT (approximately equivalent to a minor geomagnetic storm of K_p ~5) with a median variation of 20 nT in peak intensity resulting in a total *Y* value of ~870 nT when maximal. These intensity spikes presented a particularly strong cycle of ~5.50–5.70 s (within the range of Pc1 geomagnetic pulsations) as determined by FFT and wavelet transform with associated probability estimates. We also noted an average field declination of ~13.50° during baseline conditions that oscillated between ~12.70° and 13.80° during field presentation (inclination of ~77° remained unchanged). The sample time series of each magnetic field axis are presented in Fig. 1. These measurements indicated that the geomagnetic simulation field would cross the minor axis of the heart (from side-to-side of participant) as a vector oscillating back and forth within the cardiac space.

2.5. Study design

Participants contributed to both conditions (baseline and geomagnetic field) in a repeated-measures design for which each participant acted as their own control. The presentation order of these two conditions was counterbalanced in order to further account for potential differences in HRV that may simply occur over time. For order A, a baseline (BL) ECG recording was acquired for 5 min

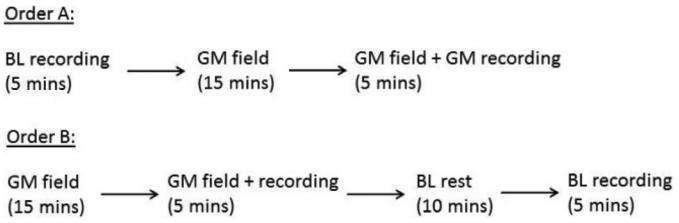
Order A:
BL recording (5 mins)
GM field (15 mins)
GM field + GM recording (5 mins)
Order B:
GM field (15 mins)
GM field + recording (5 mins)
BL rest (10 mins)
BL recording (5 mins)

Fig. 2. Outline of each condition with associated times for counterbalanced presentation; BL = baseline, GM = geomagnetic simulation.

followed by 15 min of whole-body exposure to the geomagnetic field simulation (GM) and finally an additional 5 min ECG recording during exposure. For order B, the GM condition was first applied for 15 min followed by the 5 min ECG recording while the field was still active. Afterwards, the field was terminated and 10 min were allowed to pass. Finally, a 5 min ECG recording was made for a BL condition. The procedure is further outlined in Fig. 2 along with a flow chart outlining the study from recruitment to data analysis in Fig. 3. Concomitant geomagnetic activity as indicated by three-hourly K_p index was noted for each test session. Geomagnetic data were acquired from the Solen Solar Terrestrial Activity Report (http://www.solen.info/solar/).

3. Results

All HRV variables were assessed for normality with Shapiro–Wilks test. Where normal distributions were observed, paired Student's *t*-tests were considered for comparing HRV between BL and GM conditions. However, practically all variables were non-normally distributed ($p < 0.05$) and nonparametric Wilcoxon signed rank test was instead used where associated estimates of effect size (*es*) were computed according to:

$$es = \frac{z}{\sqrt{n_1 + n_2}}$$

where n_1 and n_2 = sample size for each condition (BL + GM = 40).

Subsequent analyses revealed no significant difference between BL and GM conditions for variables *SDNN, RMSSD, VLF*, or *HF* (all $p > 0.05$). Statistically significant increases were observed for the *LF* component of HRV ($z = 2.651$, $p < 0.01$, $es = 0.419$) during the GM condition compared to BL measures with an associated relative increase for 15 out of 20 cases assessed (75%) (Fig. 4). Similarly, the *LF*/*HF* ratio also tended to increase from BL to GM with a significant difference between conditions ($z = 2.875$, $p < 0.01$, $es = 0.456$) and the associated relative increase observed for 16 out of 20 cases (80%) (Fig. 5).

The effects identified remained significant ($p < 0.01$) after removing a single case recorded during a natural geomagnetic storm ($K_p \geq 5$). Following data transformation using the natural logarithm, repeated-measures ANOVA did not indicate any significant effect of gender ($p > 0.05$) for the differences between BL and GM among HRV parameters. Descriptive statistics of all variables were computed by experimental condition and are provided in Table 1.

Table 1
Descriptive statistics for all participant heart rate variability (HRV) measures by condition including mean, median, standard deviation (SD), and interquartile range (IQR).

Group	Mean	Median	SD	IQR
Baseline (BL)				
• *SDNN*	63.98	60.57	26.37	38.20
• *RMSSD*	47.08	36.49	27.67	31.73
• *VLF*	1934.48	1073.37	2407.58	1834.82
• *LF*	1596.79	895.86	1833.14	1547.05
• *HF*	1148.07	625.28	1258.0	1359.21
• *LF*/*HF*	2.0	1.26	1.94	1.86
Geomagnetic (GM)				
• *SDNN*	71.91	66.98	30.36	34.86
• *RMSSD*	52.48	42.87	32.68	35.03
• *VLF*	2066.68	1407.35	2098.44	2231.79
• *LF*	2877.21	1550.40	3361.70	3637.89
• *HF*	1391.94	773.20	1590.71	1374.72
• *LF*/*HF*	3.32	2.72	2.71	2.82

4. Discussion

While there have been a number of essentially correlational studies investigating the potential role of geomagnetic influence on autonomic-cardiovascular state (Cornélissen et al., 2002; Dimitrova et al., 2013; Papailiou et al., 2011), the present study is among the first to begin an experimental verification of similar effects using fast frequency pulsations rather than ULF artificial fields. Although the strength of the applied field was relatively weak, similar HRV effects have been noted for an applied ULF magnetic field of only ~50 nT (Mitsutake et al., 2004). However, these previous results conversely indicated a decrease in HRV associated with the much lower frequency field and significantly longer exposure time. Although additional replications are required, the current results remain informative and tend to overlap with other relatively recent correlational results (Dimitrova et al., 2013). While we employed magnetic field simulation of sudden geomagnetic impulses, the results are nonetheless revealing when considered in light of findings from other researchers. Specifically, Dimitrova et al. (2013) previously found that *LF*/*HF* measured longitudinally from two individuals' HRV tended to increase during the two days prior to geomagnetic storms. In addition to this, the dominant periodicity of our applied magnetic field was within range of Pc1 (~0.20–4 Hz) geomagnetic pulsations (Fraser and McNabb, 1984) which have also been implicated in geomagnetic-mediated variations of HRV (Kleimenova et al., 2007). While a time lag effect was not possible in the current experiment design, our results generally supported this contention through observation of significantly increased *LF*/*HF* values during the geomagnetic simulation compared to baseline recordings. Although earlier work had conversely found an overall decrease in *LF*/*HF* for a group of volunteers during the time of increased geomagnetic activity, the authors (Dimitrova et al., 2013) suggested that participants' physiological response to geophysical processes varied according to individual biology. Furthermore, an increase in *LF*/*HF* was also found to occur during the periods following storm-level activity in earlier results (Dimitrova et al., 2013).

Despite this relative discrepancy, the earlier study upon which the current experimental verification was largely based (Dimitrova et al., 2013) also found some evidence for significant increases in the *LF* component of HRV during geomagnetic storms which was similarly observed in the current results where participants' *LF* values tended to increase during geomagnetic simulation compared to baseline measures. This factor may also be partly responsible for the presently observed ratio effects as an increase in *LF* would result in a corresponding increase of *LF*/*HF*. Although induction artifacts were not suspected given the transformation from ECG to HRV and subsequent resampling procedures, it is also evident that the observed effect was not simply an induction artifact given the discrepancy between the dominant frequency of the applied magnetic field and the band of periodicities identified for HRV effects. However, varied field strengths should also be investigated in future studies to examine potential amplitude-mediated variations of the observed effect with human participants. For the current experiment, this would have required considerably longer participant recordings and additional magnetic field exposures or a further

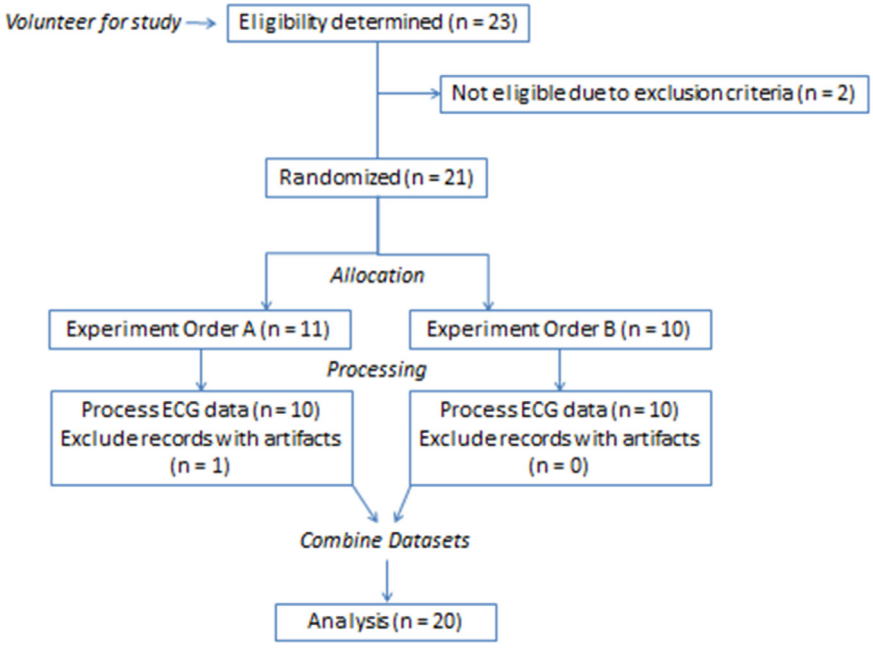
Volunteer for study
Eligibility determined (n = 23)
Not eligible due to exclusion criteria (n = 2)
Randomized (n = 21)
Allocation
Experiment Order A (n = 11)
Experiment Order B (n = 10)
Processing
Process ECG data (n = 10)
Exclude records with artifacts
(n = 1)
Process ECG data (n = 10)
Exclude records with artifacts
(n = 0)
Combine Datasets
Analysis (n = 20)

Fig. 3. Flow chart of study stages from recruitment to data analysis.

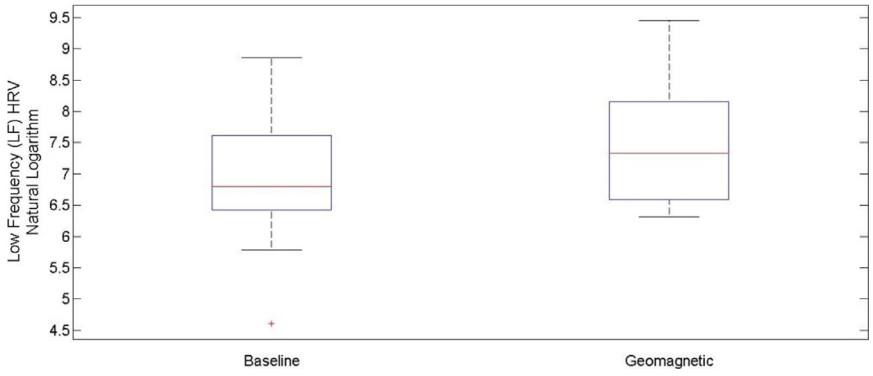

Fig. 4. Box-and-whisker plot of median low frequency (*LF*) heart rate variability (HRV) for baseline and geomagnetic conditions; data transformed to natural logarithm to reduce outlier distances ('+' sign).

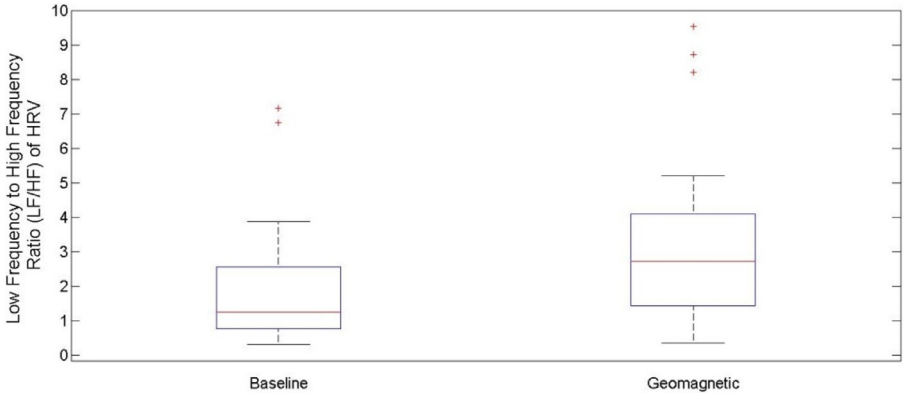

Fig. 5. Box-and-whisker plot of median low frequency to high frequency ratio (*LF*/*HF*) heart rate variability (HRV) for baseline and geomagnetic conditions; outlier cases indicated by '+'.

sample of available participants. Further research could address this concern using preliminary animal models of HRV (Supakul et al., 2014) prior to additional human testing.

Although applied magnetic fields within the Tesla range produce energies in the picojoule (pJ) range within the volume of a typical cell, the specific energy within the much smaller volumetric shell that composes the plasma cell membrane is almost a billion times less or 10^{-20} J (Persinger, 2010). This is the energy associated with the forces over the averaged separation between potassium ions that contribute the resting membrane potential as well as to the action potential in neurons (Persinger, 2010). The results obtained in the present study are more consistent with direct

effects upon the resting membrane conditions of aggregates of cells rather than direct interference with the metabolism and signaling pathways within the cells themselves.

The results of the current experiment support previous correlational work on the effects of geomagnetic influence on human cardiovascular state (Cornélissen et al., 2002; Dimitrova et al., 2009, 2013; Papailiou et al., 2011), specifically with regard to the overall state of the sympathetic and parasympathetic branches of the nervous system. In particular, the frequency components of HRV appear most susceptible to environmental electromagnetic factors, especially regarding frequencies ranging from 0.04 to 0.15 Hz. Further research is required to determine whether these apparent effects are due to geoeffective modulation of the central nervous system (Mulligan et al., 2010; Mulligan and Persinger, 2012; Saroka et al., 2014, 2016) or a direct product of autonomic-cardiovascular influence.

Acknowledgment

The authors would like to thank Suzanne Fleming for additional assistance.

References

Babayev, E.S., Allahverdiyeva, A.A., 2007. Effects of geomagnetic activity variations on the physiological and psychological state of functionally healthy humans: some results of Azerbaijani studies. Adv. Space Res. 40 (12), 1941–1951.

Billman, G.E., 2013. The LF/HF ratio does not accurately measure cardiac sympatho–vagal balance. Front. Physiol. 4 (26), 1–5.

Breus, T.K., Boiko, E.R., Zenchenko, T.A., 2015. Magnetic storms and variations in hormone levels among residents of North Polar area – Svalbard. Life Sci. Space Res. 4, 17–21.

Cook, L.L., Persinger, M.A., Koren, S.A., 2000. Differential effects of low frequency, low intensity (<6 mG) nocturnal magnetic fields upon infiltration of mononuclear cells and numbers of mast cells in Lewis rat brains. Toxicol. Lett. 118 (1–2), 9–19.

Cornélissen, G., Halberg, F., Breus, T., Syutkina, E.V., Baevsky, R., Weydahl, A., Watanabe, Y., Otsuka, K., Siegelova, J., Fiser, B., Bakken, E.E., 2002. Non-photic solar associations of heart rate variability and myocardial infarction. JASTP 64 (5–6), 707–720.

Dimitrova, S., 2006. Relationship between human physiological parameters and geomagnetic variations of solar origin. Adv. Space Res. 37 (6), 1251–1257.

Dimitrova, S., Stoilova, I., Cholakov, I., 2004. Influence of local geomagnetic storms on arterial blood pressure. Bioelectromagnetics 25 (6), 408–414.

Dimitrova, S., Mustafa, F.R., Stoilova, I., Babayev, E.S., Kazimov, E.A., 2009. Possible influence of solar extreme events and related geomagnetic disturbances on human cardio-vascular state: results of collaborative Bulgarian–Azerbaijani studies. Adv. Space Res. 43 (4), 641–648.

Dimitrova, S., Angelov, I., Petrova, E., 2013. Solar and geomagnetic activity effects on heart rate variability. Nat. Haz. 69 (1), 25–37.

Fraser, B.J., McNabb, P.W., 1984. The recording of Pc1 geomagnetic pulsations using a microcomputer preprocessing system. Geophys. Surv. 6, 249–258.

Grinsted, A., Moore, J.C., Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Proc. Geophys. 11, 561–566.

Jevrejeva, S., Moore, J.C., Grinsted, A., 2003. Influence of the Arctic Oscillation and El Niño-Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: the wavelet approach. J. Geophys. Res. 108 (D21), 4677.

Kaufmann, T., Sütterlin, S., Schulz, S.M., Vögele, C., 2011. ARTiiFACT: a tool for heart rate artifact processing and heart rate variability analysis. Behav. Res. Meth. 43 (4), 1161–1170.

Kleimenova, N.G., Kozyreva, O.V., Breus, T.K., Rapoport, S.I., 2007. Pc1 geomagnetic pulsations as a potential hazard of the myocardial infarction. JASTP 69 (14), 1759–1764.

Lagace, N., St-Pierre, L.S., Persinger, M.A., 2009. Attenuation of epilepsy-induced brain damage in the temporal cortices of rats by exposure to LTP-patterned magnetic fields. Neurosci. Lett. 450 (2), 147–151.

Mach, Q.H., Persinger, M.A., 2009. Behavioral changes with brief exposures to weak magnetic fields patterned to stimulate long-term potentiation. Brain Res. 1261, 45–53.

Michaud, L.Y., Persinger, M.A., 1985. Geophysical variables and behaviour XXV: alterations in memory for a narrative following application of theta frequency electromagnetic fields. Percept. Motor Skills 60, 416–418.

Mitsutake, G., Otsuka, K., Oinuma, S., Ferguson, I., Cornélissen, G., Wanliss, J., Halberg, F., 2004. Does exposure to an artificial ULF magnetic field affect blood pressure, heart rate variability and mood. Biomed. Pharmacother. 58, 20–27.

Mulligan, B.P., Persinger, M.A., 2012. Experimental simulation of the effects of sudden increases in geomagnetic activity upon quantitative measures of human brain activity: validation of correlational studies. Neurosci. Lett. 516 (1), 54–56.

Mulligan, B.P., Hunter, M.D., Persinger, M.A., 2010. Effects of geomagnetic activity and atmospheric power variations on quantitative measures of brain activity: replication of the Azerbaijani studies. Adv. Space Res. 45 (7), 940–948.

Murugan, N.J., Karbowski, L.M., Lafrenie, R.M., Persinger, M.A., 2013. Temporally-patterned magnetic fields induce complete fragmentation in planaria. PLOS One.. http://dx.doi.org/10.1371/journal.pone.0061714.

Oinuma, S., Kubo, Y., Otsuka, K., Yamanaka, T., Murakami, S., Matsuoka, O., Ohkawa, S., Cornélissen, G., Weydahl, A., Holmeslet, B., Hall, C., Halberg, F., 2002. On behalf of the "ICEHRV" Working Group: graded response of heart rate variability associated with an alteration of geomagnetic activity in a subarctic area. Biomed. Pharmacother. 56, 284–288.

Otsuka, K., Cornélissen, G., Weydahl, A., Holmeslet, B., Hansen, T.L., Shinagawa, M, Kubo, Y., Nishimura, Y., Omori, K., Yano, S., Halberg, F., 2001a. Geomagnetic disturbance associated with decrease in heart rate variability in a subarctic area. Biomed. Pharmacother. 55, 51–56.

Otsuka, K., Oinuma, S., Cornélissen, G., Weydahl, A., Ichimaru, Y., Kobayashi, M., Yano, S., Holmeslet, B., Hansen, T.L., Mitsutake, G., Engebretson, M.J., Schwartzkopff, O., Halberg, F., 2001b. Alternating-light-darkness-influenced human electrocardiographic magnetoreception in association with geomagnetic pulsations. Biomed. Pharmacother. 55, 63–75.

Papailiou, M., Mavromichalaki, H., Kudela, K., Stetiarova, J., Dimitrova, S., 2011. Effect of geomagnetic disturbances on physiological parameters: an investigation on aviators. Adv. Space Res. 48, 1545–1550.

Persinger, M.A., 2010. 10^{-20} Joules as a neuromolecular quantum in medicinal chemistry: an alternative approach to myriad molecular pathways? Curr. Med. Chem. 17 (27), 3094–3098.

Persinger, M.A., Saroka, K.S., 2013. Comparable proportions of classes of experiences and intracerebral consequences for surgical stimulation and external application of weak magnetic field patterns: implications for converging effects in complex partial seizures. Epilepsy Behav. 27 (1), 220–224.

Saroka, K.S., Caswell, J.M., Lapointe, A., Persinger, M.A., 2014. Greater electroencephalographic coherence between left and right temporal lobe structures during increased geomagnetic activity. Neurosci. Lett. 560, 126–130.

Saroka, K.S., Vares, D.E., Persinger, M.A., 2016. Similar spectral power densities within the Schumann resonance and a large population of quantitative electroencephalographic profiles: supportive evidence for Koenig and Pobachenko. PLoS One 11 (1), e0146595. doi:10.1371/journal.pone.0146595.

Stoupel, E., 1999. Effect of geomagnetic activity on cardiovascular parameters. J. Clin. Basic Cardiol. 2 (1), 34–40.

Supakul, L., Pintana, H., Apaijai, N., Chattipakorn, S., Shinlapawittayatorn, K., Chattipakorn, N., 2014. Protective effects of garlic extract on cardiac function, heart rate variability, and cardiac mitochondria in obese insulin-resistant rats. Eur. J. Nutr. 53, 919–928.

Yun, S.H., Mook-Jung, I., Jung, M.W., 2002. Variation in effective stimulus patterns for induction of long-term potentiation across different layers of the rat entorhinal cortex. J. Neurosci. 22, 1–5.